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Analytical Studies of Transient Film-Cooling Effectiveness

in Gun Barrels

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An analytical model has been developed for two problems of gun-barrel cooling: (a) film cooling with wear reducing additives and (b) liquid film cooling. The governing equations were derived from an integral method and the solutions of the film-cooling effectiveness were obtained by application of the characteristic method. The results found earlier are: (a) with the additives, the effectiveness is very significant in a region where the erosion is most series and (b) with liquid cooling, the effectiveness is in general high. It is, however, smaller in that region.

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INTRODUCTION

This report concerns the analytical studies of film cooling in gun barrels (Grant No. DAAG29-76-G-0008, Formerly DAHC04-74-G-0191) during the period October 1, 1974 to December 31, 1976. The studies include two areas, namely cooling with wear reducing additives and liquid cooling. The dimensionless wall enthalpy distribution referred to as film-cooling effectiveness has been obtained for each area. In this section, a statement of the problems and a list of publications are given. In the ensuing sections, important results from the analyses will be summarized followed by a description of experimental design. Finally, extension of the present work will be discussed.

Two areas of study just mentioned are: 1) Cooling with wear reducing additives (film cooling in stationary coordinates) - Consider a layer of the ablative polymeric additive wrapping around the propelling charges. When the high temperature gases are produced during the process of combustion, the additive degrades to form a cool gas film that flows along the barrel and separates the high temperature core flow from the barrel surface. The cooling effect is thus obtained. This cooling scheme gives the high film-cooling effectiveness in the region adjacent to the position of shot start where the erosion is most series; 2) Liquid cooling (film cooling in a moving coordinate) In this cooling scheme, a small amount of liquid is confined to the inside of the projectile. When the projectile moves under high pressure, the liquid is squeezed out to cool the boundary layer. For an observer moving with the projectile, he sees that the coolant flows out from a fixed location into the unsteady turbulent boundary layer. In this way, the problem may be regarded as film cooling in a moving

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coordinate. Liquid cooling technique is very limited in the
current literature. The cooling effect, however, appears high.
The prediction of the film-cooling effectiveness in both two areas
is our essential goal for this project.

There are three publications resulting from the investi-
gation under the Grant. They are listed in Table I. The first
two and third in the table treat the problems in the first area
(cooling with wear reducing additives) and the second area (liquid
cooling) respectively. The second one can be considered an improved
version of the first one since the former gives the precise treatment
of the momentum equation.

Table I

List of Publications

1. Tsou, F. K., "Film Cooling in Gun Barrels", presented at the First International Symposium on Ballistics, Orlando, Florida, November, 1974 and published in the proceedings.

2. Tsou, F. K., "Prediction of Film-Cooling Effectiveness in an Unsteady Turbulent Boundary Layer," ASME paper No. 76-HT-28, presented at the National Heat Transfer Conference, St. Louis, Mo., August, 1976.

3. Tsou, F. K. and [*]Varghese, T., "Film Cooling with Injection from a Moving Projectile," published in the Proceedings of the Second International Symposium on Ballistics, Daytona Beach, Florida, March, 1976.

[*] Varghese started as a post-master student in January, 1975 and passed his candidacy examination in May, 1976. He is currently a Ph.D. candidate in the Department of Mechanical Engineering and Mechanics, Drexel University.

Important Results

Prior to summarizing the results, a brief description of the approach used in the investigation is given here. To study the problem of heat transfer, it is often convenient to define a heat transfer coefficient, h in the following form:

$$q = h \ (T_w - T_{ref}) \tag{1}$$

To utilize this definitive expression, one needs to know h and the reference temperature, T_{ref}. If the adiabatic wall temperature, T_{aw} is used as T_{ref}, h for the cases with film cooling and without film cooling is approximately the same. Since h for the case without film cooling is considered available, the prediction of T_{aw} thus becomes the center of interest in a film-cooling problem. In the present work, the dimensionless enthalpy known as film-cooling effectiveness defined below is used,

$$\eta = \frac{h_{aw}(x,t) - h_{\infty}(x,t)}{h_i - h_{\infty} (x,t)} \tag{2}$$

where the subscripts, aw,∞, i are referred to the condition of adiabatic wall, free stream, and injection respectively. The determination of η is therefore the essential undertaking of this project. Employing typical assumptions, the governing integral equation can be recast into three first order equations that are hyperbolic. The method of characteristic is then applied to obtain the solution of η. The results of calculation from the publications mentioned in the foregoing are as follows:

1) Cooling with wear reducing additives

Fig. 1 shows the effectiveness η versus the dimensionless distance x/x_1 with time in milli-second as a parameter. All curves start from the position of shot start, x/x_1. At early times (t =0.2 and 0.3 msec), n decreases monotonically. After 0.3 msec, the rate of ablation decreases and reduces to zero at t = 0.5 msec. Thus for t = 0.4 msec, increases η first and then decreases. The curves for

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t = 0.5 and 0.7 msec have the similar nature. At t = 0.5 msec, $\eta = 0$ at $x/x_1 = 1$. The effectiveness η at t = 0.7 msec remains zero until $x/x_1 = 1.4$. These results indicate that, at earlier times, the cooling effect is very significant in the region where the erosion is most series.

2) Liquid Cooling

A similar plot in a stationary coordinate is shown in Fig. 2. The curves again were plotted from the position of shot start. At t = 0.2 and 0.5 msec, η increases and reaches to unity at the base of the projectile. The third curve at t =1 msec shows a gradual decrease first and then an increase to $\eta = 1$ at the base. Like curves in Fig. 1, there is a point of discontinuity on each curve. The gradual decrease in the region of small x is probably caused by the assumptions used in the analysis. Generally speaking, the effectiveness of liquid cooling is fairly high. However, in the problems of gun barrel cooling, one requires better cooling effect near the position of the shot start. The trend shown in Fig. 2 is just opposite.

With the results of the effectiveness just mentioned, one is able to calculate the erosion of a surface. For example, in the case of one-dimensional melting of a solid with complete removal of meet, Goodman's integral method can be conveniently applied. The required surface heat flux in this method is obtained from Eq. (1), in which the heat transfer coefficient h is given and the adiabatic wall temperature, T_{aw} is computed from the present solution.
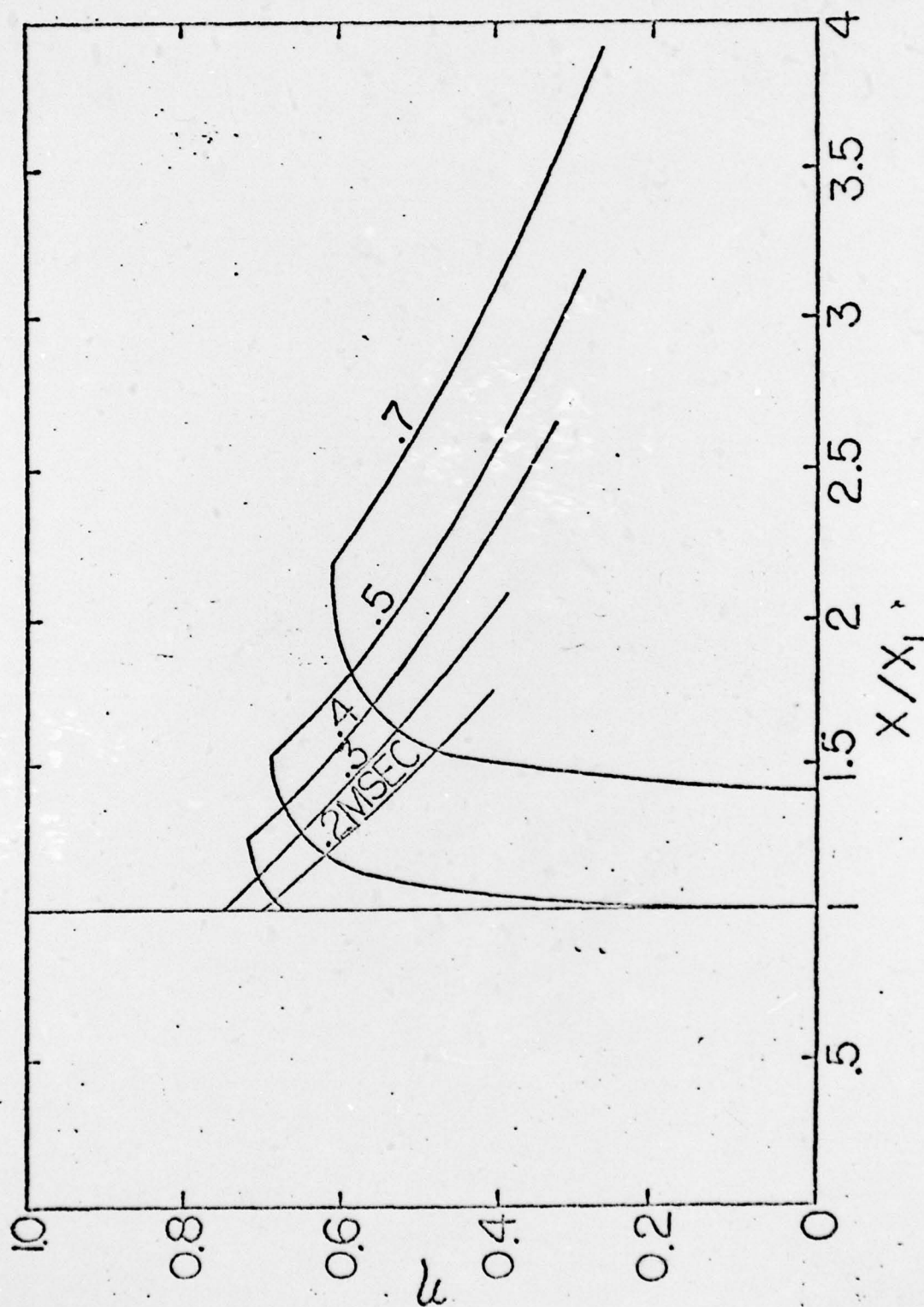
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Figure 1. Film cooling effectiveness η, versus dimensioness dostance. x/x_1. (x_1 = length of the injection slot.) -- Cooling with wear reducing additives.
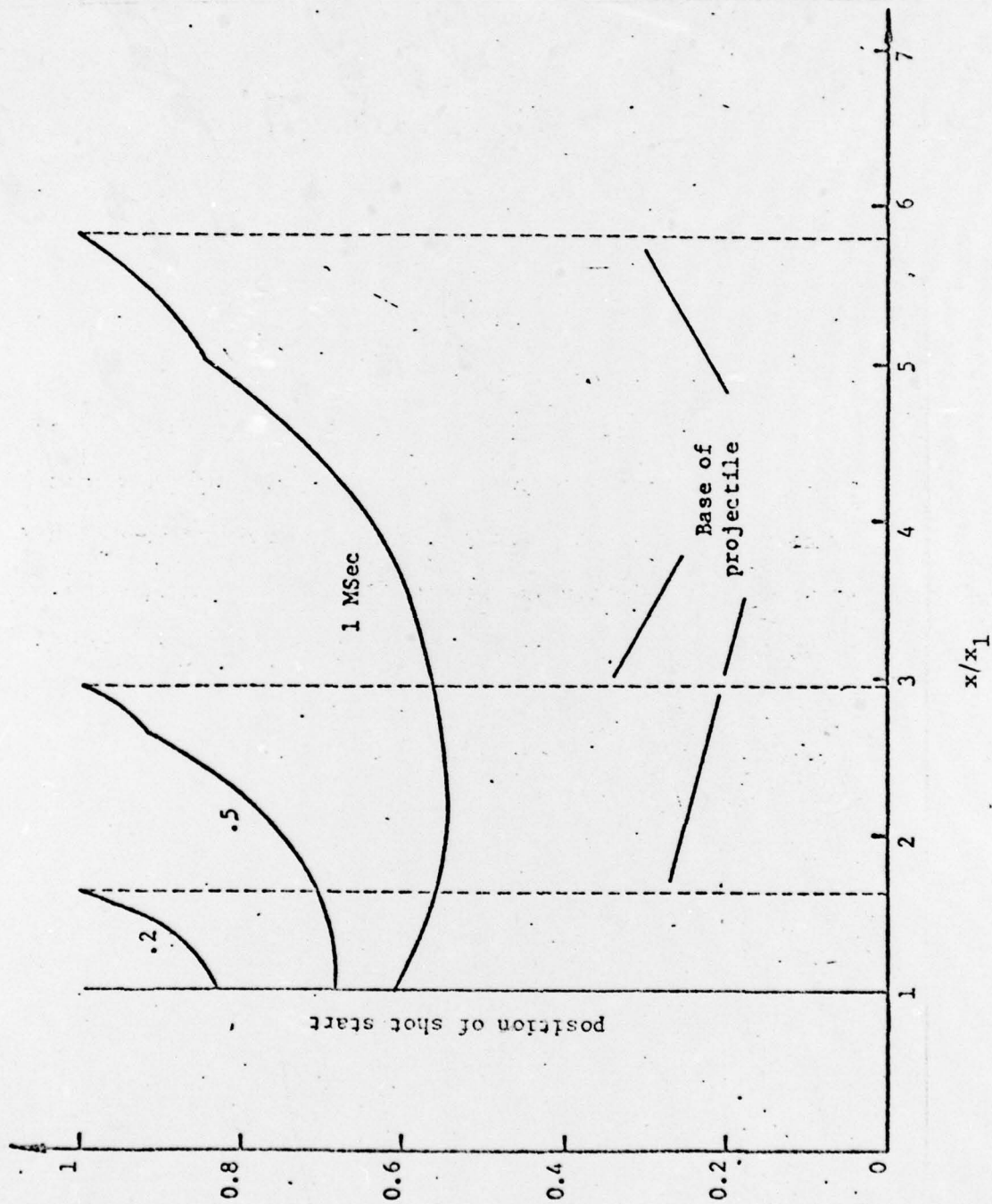
Fig. 2 Film-cooling Effectiveness versus Dimentionless Distance (x_1= 0.0290m) -- liquid cooling.

Experimental Design

Experimental work using gun barrels are available in the literature. The fact that, in the gun barrel measurements, the ablative rate of the additives is difficult to control preclude comparison with the present analytical results. To substantiate these results, it is felt that the use of an intermittent subsonic wind tunnel, known as Ludweig Tube, would be appropriate. The tube consists of a conventional shock tube with the insertion of a converging-diverging nozzle into the section upstream of its diaphragm. A transient subsonic flow in a period of several milli-seconds can be obtained in the test section. The injection system including a quick closing valve mechanism will give desired injection mass flow. In this way, the transient film-cooling effectiveness can be measured. Some details of the experimental method are given in Appendix. The method applied to the condition that is relevant to cooling with wear reducing additives.

Discussion and Conclusion

Extension of the present work other than the experimental measurements just-described is given here. The discussion is again limited to the case of cooling with wear reducing additives.

The problems that remain to be studied are: 1) The boundary layer may be destroyed initially so as to give no cooling effect. 2) To study the ablative rate, one has to consider the parameters: the location, length, and thickness of the linear. Some new models or modification of the present models need to be developed. 3) The density of the ablative materials may be another parameter. A study based on the diffusion thermal effect would give an answer. 4) The

use of flaps has shown in improvement in cooling effect. Analytical study of transient flow and heat transfer over such flaps can be made.

The ultimate goal for the present studies is to obtain information on the inert erosion of gun barrel surfaces. As mentioned earlier, it is convenient to solve one dimensional phase change problems with a proper numerical scheme. Since the axial heat conduction is significant, it would be more important to solve two-dimensional problems.

The approach used in the present study may have other applications, e.g. film cooling along gas turbine blades. Here, the problems of interest include the process of start-up, shut-down and the period of load change as well as the wake effect. The transient response of blade surface temperature will contribute to the thermal fatigue and creep of the blade material significantly.

Appendix †

This appendix describes how experimental determination of film-cooling effectiveness can be performed. Consider gas injection into the subsonic turbulent boundary layer on a flat, adiabatic wall. The following six combinations of injection gas mass flow rate, $\overset{o}{m}_i$, and free stream gas velocity, U_∞ can be studied.

(1) $\overset{o}{m}_i$ = const. $\qquad\qquad$ U_∞ = const.

(2) $\overset{o}{m}_i$ = $\overset{o}{m}_i(t)$ $\qquad\quad$ U_∞ = const.

(3) $\overset{o}{m}_i$ = const. $\qquad\qquad$ U_∞ = $U_\infty(t)$

(4) $\overset{o}{m}_i$ = $\overset{o}{m}_i(t)$ $\qquad\quad$ U_∞ = $U_\infty(t)$

(5) $\overset{o}{m}_i$ = const. $\qquad\qquad$ U_∞ = $U_\infty(x,t)$

(6) $\overset{o}{m}_i$ = $\overset{o}{m}_i(t)$ $\qquad\quad$ U_∞ = $U_\infty(x,t)$

Each of these cases is qualitatively shown in Fig. A1. The techniques used to obtain free stream flow and injection flow as well as film-cooling effectiveness measurements are described in the following:

(1) <u>Subsonic flow production technique</u>. Use is made of an intermittent subsonic wind tunnel that consists of a conventional shock tube with the insertion of a converging-diverging nozzle into the section upstream of the diaphragm (high pressure section). Such a device is known as Ludweig Tube. The operating stages of this tube are shown in Fig. A2, an x-t diagram and the sketch of the tube.

Referring to Fig. A2, when the diaphragm is broken at time zero, a shock wave followed by a contact surface travels downstream into the low pressure gas. Upstream of the diaphragm, an expansion

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† The author is indebted to Professor L. T. Smith, Department of Mechanical Engineering and Mechanics, Drexel University, for his important contribution to this appendix.

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wave propagate into a high pressure gas, accelerating it toward the nozzle exit. During this initial starting period, we have $U_\infty = U_\infty(x,t)$ in the subsonic test section of the nozzle, and at a given location, the variation of velocity with time is as shown in Fig. A1 (a and b). As soon as the nozzle throat becomes choked, as determined by the ratio of nozzle throat area to supply tube area, the remaining part of the expansion wave is swept downstream. In the supply tube, the strength, or pressure ratio, of the expansion wave becomes fixed. Thus, a region of constant gas properties and velocity is created between the expansion wave and the nozzle inlet. This region serves as the supply condition for a steady expansion flow through the nozzle, with $U_\infty = $ const. in the subsonic test section as shown in Fig. A1 (c and d). Steady flow lasts until the expansion wave reflectes from the end wall of the supply tube and returns to the nozzle inlet. At this stage in the operation, the expansion wave reflects from the nozzle and propagates back upstream into the supply tube to produce a second period of steady nozzle flow with altered free stream conditions. Subsequent expansion wave reflections between the nozzle and supply tube end wall produce additional periods of steady nozzle flow as illustrated in Fig. A1 (e and f). We thus have the case $U_\infty = U_\infty(t)$. Finally, a reflected shock system returns to the nozzle from the low pressure tube to destroy the periodic nozzle flow pattern.

For each of these experiments, nozzle free stream velocity and gas properties will be computed using existing theory. These calculations will be verified by comparing measured static pressure in the test section to predicted values. Moreover, measurements of

the static pressure will be used to adjust the theoretical calculations to account for the effects of the viscous boundary layer and thus arrive at an accurate determination of the free stream conditions in the test section.

For the initial transient flow period, with $U_\infty = U_\infty(x, t)$, the governing equations of motion will be solved numerically, using the method of characteristics, to determine free stream conditions as a function of time at a given location in the nozzle test section [1,2]. Existing analytic solutions [3] will be used to compute test times and free stream conditions during the initial steady flow period, U_∞ = const., and during the periodic flow, $U_\infty = U_\infty(t)$.

(2) <u>Gas Injection Technique</u>. The gas injection system can be modeled after the Oxford system [4, 5], however, certain modifications have to be made in order to achieve transient injection with $\overset{o}{m}_i = \overset{o}{m}_i(t)$. Referring to Rig. A3, injection gas will be held in a chamber of volume V at pressure p_i. Before the start of an experiment, the chamber will be sealed off from the channel leading to the injection slot in the nozzle test section by means of a thin Mylar diaphragm. Injection will be started by bursting the diaphragm with a needle activated by a solenoid. A current pulse of 3000 amps with a rise time 200 μs [4,5] will be used to activate the solenoid, and will be triggered by a pressure pulse generated by the shock wave which travels into the low pressure dump tube section of the tunnel. A time delay system will be provided to control the time of the start of gas injection, and the design will allow injection to be started prior to the free stream flow in the test section.

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For steady gas injection, $\overset{o}{m}_i$ = const., the injection system will be operated without the quick shut-off valve shown in Fig. A3.

The injection mass flow rate will be determined by measuring the time rate of change of the injection pressure dp_i/dt, during the run [4]. For the short injection times involved (10 to 15 milliseconds), the process within the injection gas reservoir can be assumed adiabatic. The injection mass flow rate is then given by

$$\overset{o}{m}_i = \frac{V}{\gamma R T_i} \frac{dP_i}{dt}$$

where γ is the ratio of specific heats of the injection gas, R is the gas constant, and T_i is the injected gas temperature. For small reservoir pressure drops, the injection gas temperature, T_i, may be considered constant [4]. The gas temperature at the point of injection into the turbulent boundary layer is taken to be equal to T_i, and this assumption can be checked using a thin film temperature gage mounted flush to the channel conducting gas from the reservoir to the injection slot, as shown in Fig. A3.

For transient gas injection, $\overset{o}{m}_i = \overset{o}{m}_i(t)$, a quick shut-off valve will be mounted on the diaphragm bursting needle as shown in Fig. A3. With this configuration, one can first have several milliseconds of steady injection followed by a rapid decrease in injection mass flow rate with time as shown in Fig. A1 (b, d and f).

(3) _Film cooling effectiveness measurements_. During the short testing times involved in the operation of the Ludwieg tube, there is not enough time for appreciable heat transfer into the test section nozzle blocks. We thus deal with the case of injection into the turbulend boundary layer over an adiabatic wall. The effectiveness has

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been defined as the dimensionless adiabatic wall enthalpy (see Eq. 2 in the text). For the case of injection gas and free stream gas of the same chemical species, and assuming both to be an ideal gas with constant specific heats, the effectiveness becomes

$$\eta(x,t) = \frac{T_{aw} - T_\infty}{T_i - T_\infty}$$

where T_{aw} is the adiabatic wall temperature, and T_∞ and T_i are the temperatures of the free stream gas flow and injection gas respectively. With both T_i and T_∞ determined by the methods discussed previously, it remains to experimentally determine adiabatic wall temperature in order to determine η.

Platinum thin resistance gages will be used to measure adiabatic wall temperature as a function of time at several locations upstream and downstream of the gas injection port. The gages [6] consist of a pyrex or quartz insulating material mounted flush with the wall surface. The surface temperature of the insulating material is measured by a thin platinum film in good thermal contact with the surface. The thickness of the film is of the order of one micron. A constant current is passed through the film such that measurement of the voltage across the film enables the resistance and hence the surface temperature to be determined. The rise time of such gages are typically of the order of 10 microseconds [4], two orders of magnitude less than the expected testing time of the experiments.
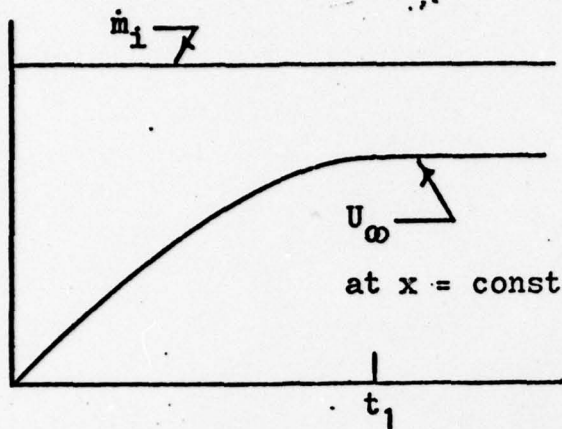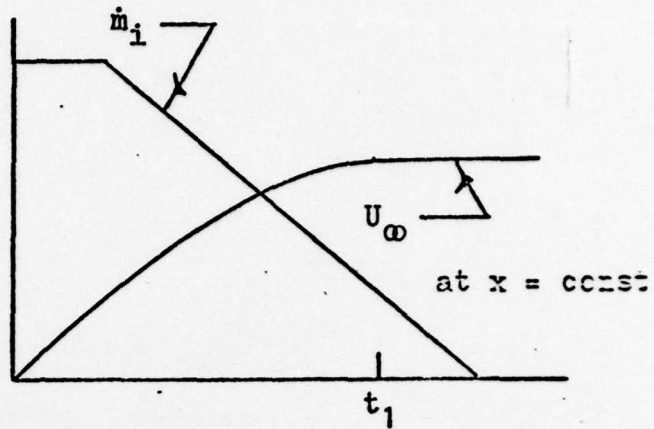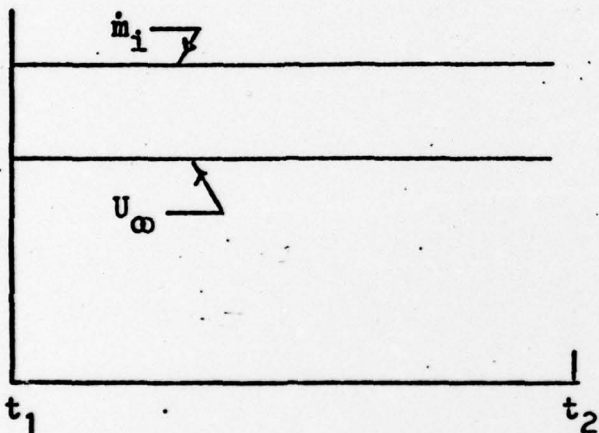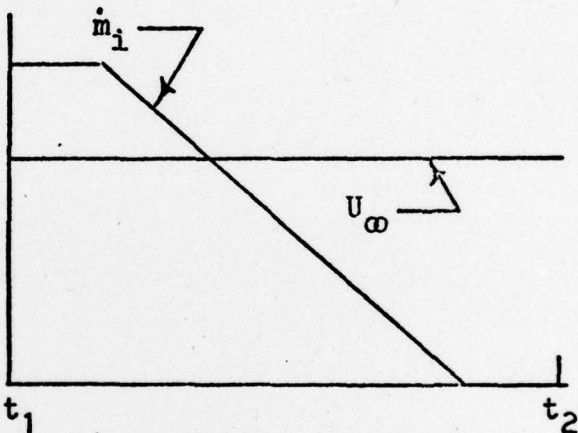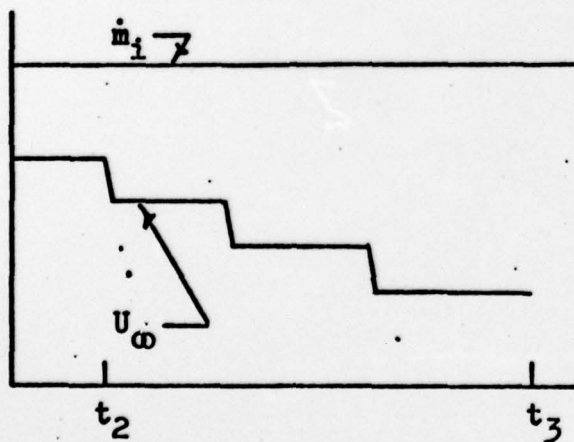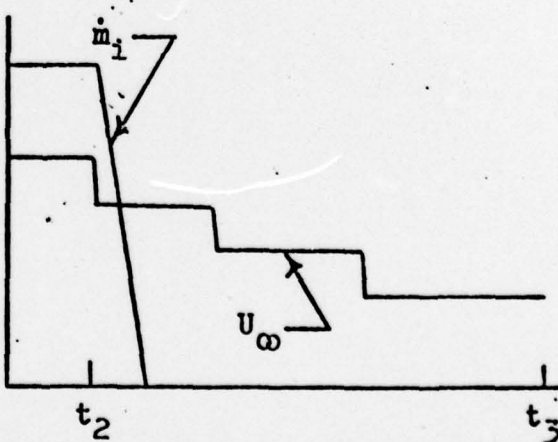
Figure A1. Combinations of free stream velocity, U_∞, and injection gas mass flow rate, $\dot{m}_i$, versus time. Typical time scales shown are: $t_1 = 4$ ms, $t_2 = 16$ ms, $t_3 = 70$ ms.
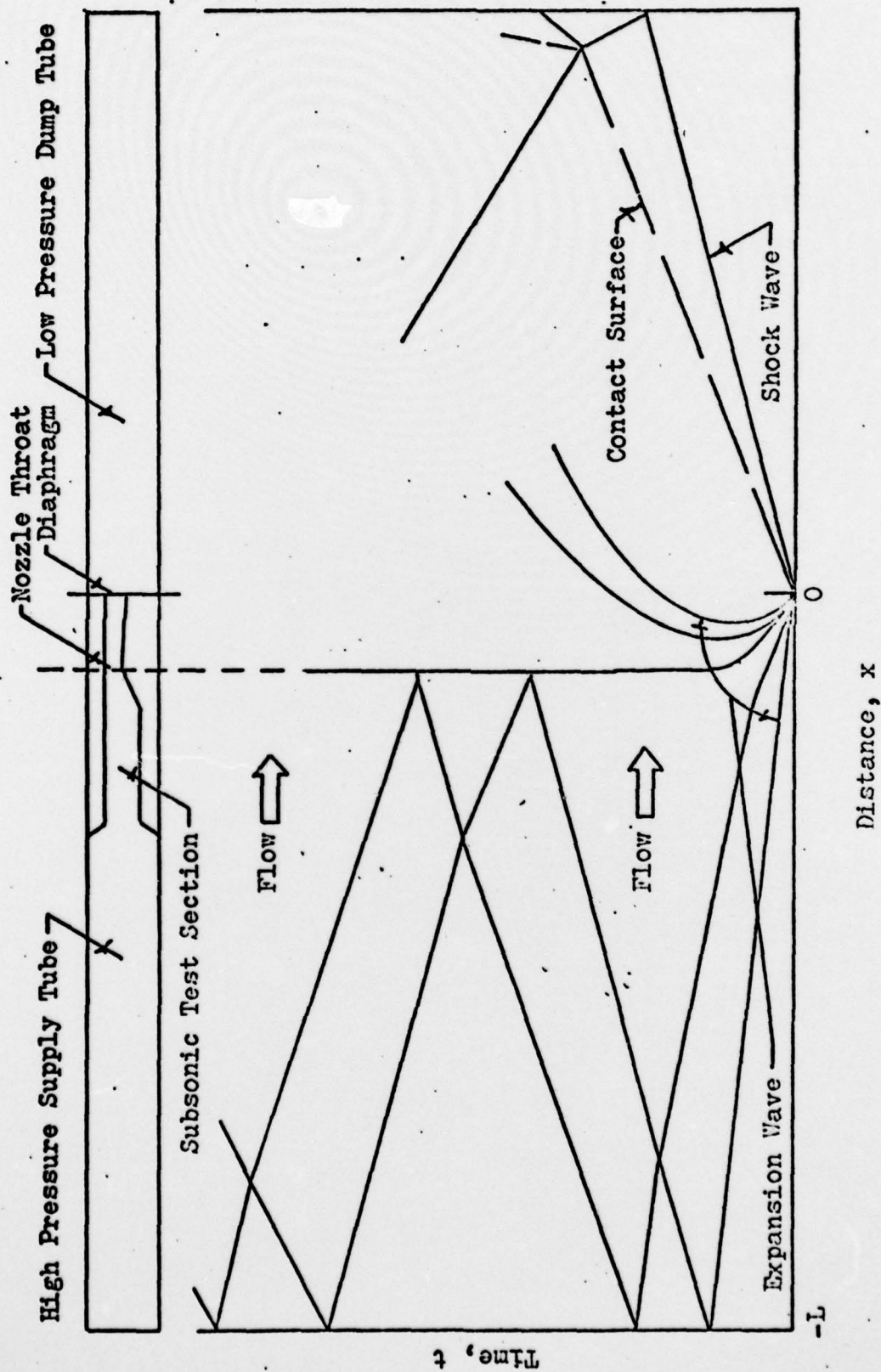
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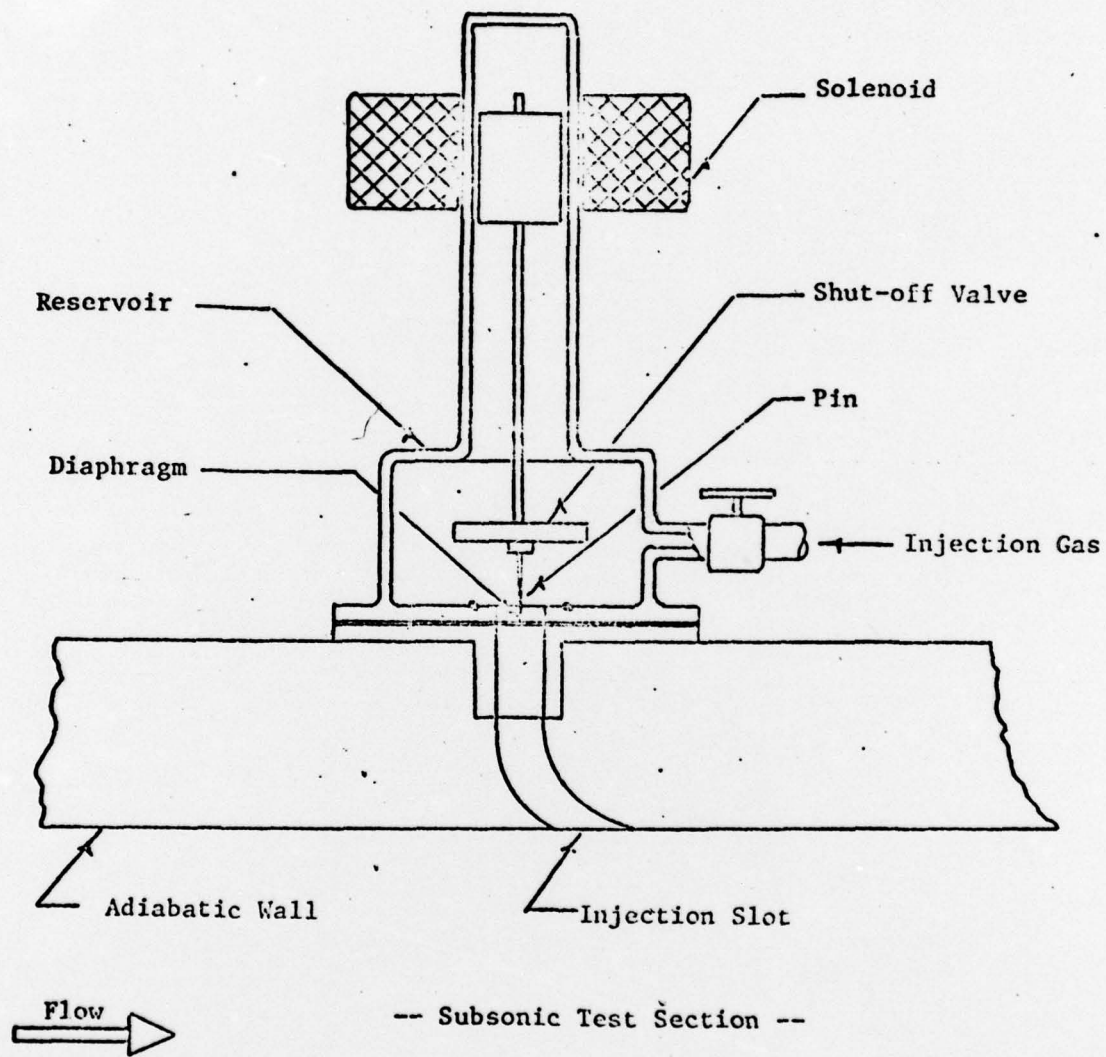Figure A2. The Ludwieg Tube intermittent wind tunnel: sketch and simplified x-t diagram.

Figure A3. Gas Injection System

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